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REPORT NO.
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Variation of Dislocation Density and Stored Energy with Grain Size

13 MARCH 1963

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Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION
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ABSTRACT

The stored energy of metals (due to the dislocation density resulting from deformation) increases for a given strain as grain size decreases. This variation with grain size becomes less as the strain increases.

This report explains this variation of dislocation density with grain size in terms of the average distance the dislocations move during deformation. Dislocation densities, which are in good agreement with densities counted from electron transmission micrographs, are calculated on the basis of this interpretation. It is also found that the variation with strain of the average distance of dislocation motion is in agreement with the observed change in deformation cell size with strain.

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I. INTRODUCTION

A small percentage of the energy expended in plastically deforming a metal remains "stored" in the metal, causing an increase in internal energy. This increment in internal energy is associated with the defects generated during deformation.

In a plastically deformed polycrystal, it is to be expected that the distribution and density of dislocations are functions of the grain size, with higher dislocation densities occurring in fine-grained than in coarse-grained aggregates at the same strain. On this basis, the stored energy should be a sensitive function of the grain size, particularly at low strains. Both the stored energy and the manner in which the stored energy is released depend on the grain size.

In Ref. 1 it is shown that the stored energy of metals (due to the dislocation density resulting from deformation) increases for a given strain as grain size decreases, for small strains. It then becomes relatively independent of grain size for large strains (Ref. 1, Figs. 10 and 12).

This report explains this variation of dislocation density with grain size in terms of the average distance moved by dislocations. Dislocation densities, which are in good agreement with densities counted from electron transmission micrographs, are calculated on the basis of this interpretation. Also, it is found that the variation with strain of the average distance of dislocation motion is in agreement with the observed change in deformation cell size with strain.

II. DISCUSSION

The plastic strain ϵ in a deformed metal is given by

$$\epsilon = \alpha_1 \rho b s \tag{1}$$

where α_1 is a geometric constant (value 1.4) relating tensile strain to shear strain, ρ is the density of dislocations that have participated in the deformation, and s is the average distance they have moved. Furthermore, the data of Keh and Weissman (Ref. 2) on the effect of strain and grain size on dislocation density in iron suggest that (Ref. 3)

$$s \approx kd^n \tag{2}$$

where d is the average grain diameter and n and k are constants that vary with strain (Fig. 1). Substituting Eq. 2 into Eq. 1 and solving for ρ, one obtains

$$\rho = \left(\frac{\epsilon}{k_1 b}\right)\left(\frac{1}{d^n}\right) \tag{3}$$

where $k_1 = \alpha_1 k$. Assuming that the stored energy released during recrystallization is proportional to dislocation density, one obtains a similar expression for stored energy E:

$$E = \left(\frac{\epsilon}{k_2 b}\right)\left(\frac{1}{d^n}\right) \tag{4}$$

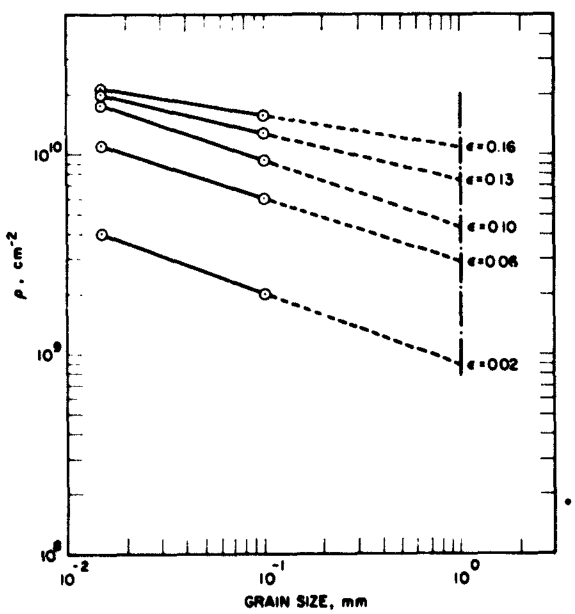

FIG 1. DISLOCATION DENSITY ρ VERSUS GRAIN SIZE FOR IRON STRAINED VARIOUS AMOUNTS (DATA FROM KEH AND WEISSMAN)

From Fig. 1 it is seen that, as strain increases, both n and k_1 (obtained from the value of ρ at d = 1 mm) decrease. Similar behavior is shown for stored energy data (Ref. 4) on compressed copper in

Fig. 2.[1] A plot of n (the slope of the dislocation density or stored energy versus grain size plot) as a function of strain is given in Fig. 3. It is seen here that the data for both iron and copper fit a smooth curve, (with n decreasing from about 0.4 at 2 percent strain to zero at 50 percent strain) suggesting that n in Eqs. 2-4 is independent of the metal or crystal structure being deformed. It also supports the assumed relationship between stored energy of recrystallization and dislocation density.

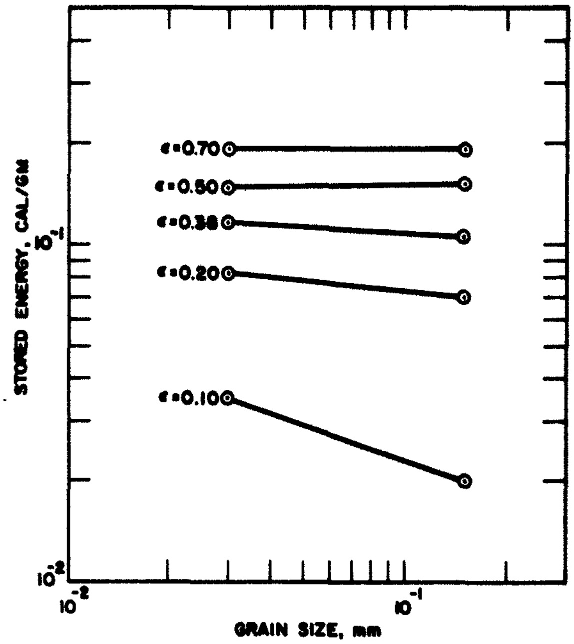

FIG 2. STORED ENERGY VERSUS GRAIN SIZE FOR COPPER COMPRESSED VARIOUS AMOUNTS (CORRECTED DATA FROM CLAREBROUGH et al)

The factor k appearing in Eq. 2 is obtained from the intercept at d = 1 mm in Fig. 1. The values so obtained are plotted as a function of strain in Fig. 4.

The following interpretation can be offered for the factors k and d^n in the expression $s = kd^n$. Since the factor d^n increases with strain, this factor is probably related to the expansion of a dislocation loop with strain. The fact that this expansion for low strains is less, the smaller the grain size, suggests that a larger number of small loops are formed in the fine-grained materials. Since there is now considerable evidence indicating that grain

[1] The corrected values of stored energy plotted in Fig. 2 are obtained by multiplying the total stored energy released during annealing by the factor $(1 - E_r/E)$ taken from Gordon's data (Ref. 5). E_r is the stored energy associated with recovery and E is the total energy released during annealing.

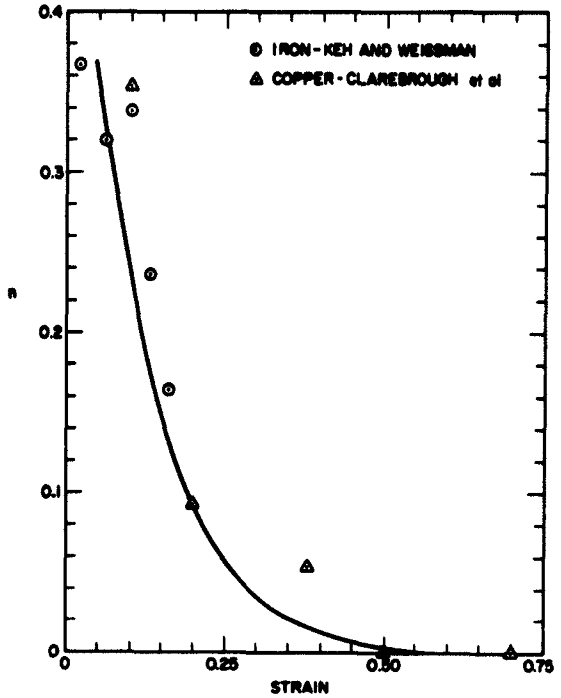

FIG 3. VARIATION OF THE EXPONENT n WITH STRAIN

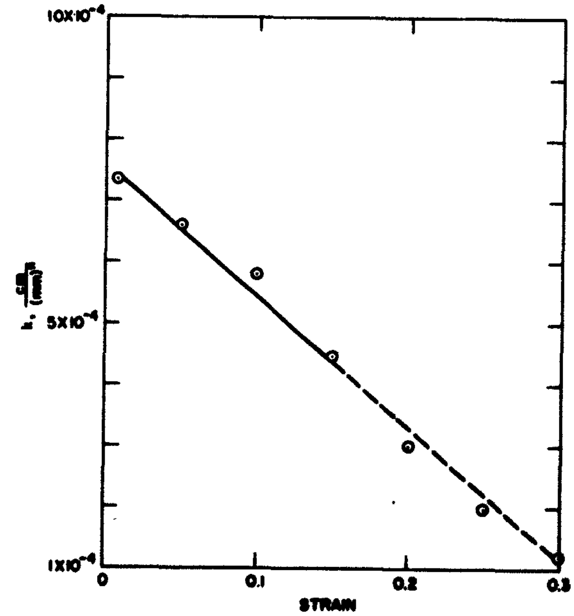

FIG. 4 VARIATION OF THE FACTOR k WITH STRAIN (DATA FROM KEH AND WEISSMAN)

boundaries supply dislocations during deformation, it is reasonable to expect that for the same strain, the fine-grained material will contain more and smaller dislocation loops than a coarser-grained metal.

Since k decreases with an increase in strain, this factor is probably related to the obstacles which can prevent the further expansion of a loop. Initially the expansion of a loop is only restricted by the grain boundary or perhaps the annealed substructure, which in turn may be related to the grain size. However, with an increase in strain, dislocation tangles occur and a deformation substructure or cell structure develops, which interferes with the further expansion of a dislocation loop and reduces its free path below the inter-grain boundary distance. Hence, k may be related to the dislocation tangle or cell structure which forms during deformation.

Figure 5 shows how $s = kd^n$ varies with strain. It is seen here that the average distance of dislocation motion increases with strain to about 10 percent or 12 percent strain and

then decreases with further strain. Of interest in this regard is the fact that a well-defined substructure first forms in iron at approximately this value of strain (Ref. 2). Hence it appears that the variation of s with strain is related to the formation of the deformation cell structure. The magnitude of s is in accord with this suggestion. Furthermore, if one calculates s_i for each 1 percent increment of strain, $\Delta\epsilon_i$, by the relation

$$s_i = \frac{\Delta\epsilon_i}{\alpha_1 \rho_i b} \qquad (5)$$

and assumes that $\rho_i = 0.1\,\rho_t$ (where ρ_t is the total dislocation density at each value of strain), one obtains a variation of s_i with strain for iron[2] that is in good agreement with the observed change in deformation cell size with strain (Fig. 6).

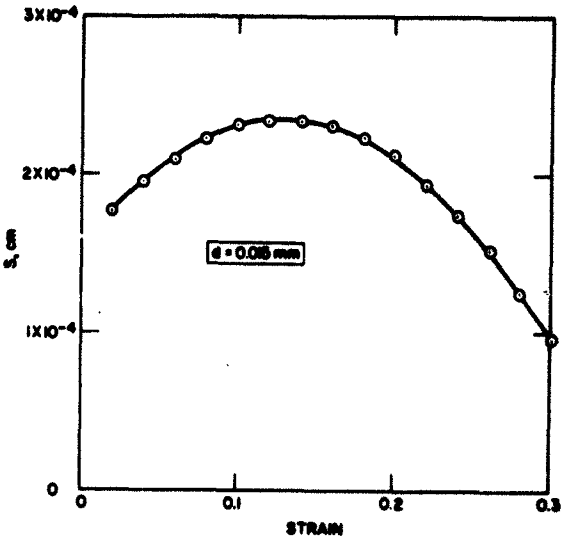

FIG. 5. VARIATION OF THE AVERAGE DISTANCE MOVED BY THE DISLOCATIONS AS A FUNCTION OF STRAIN (DATA FROM KEH AND WEISSMAN)

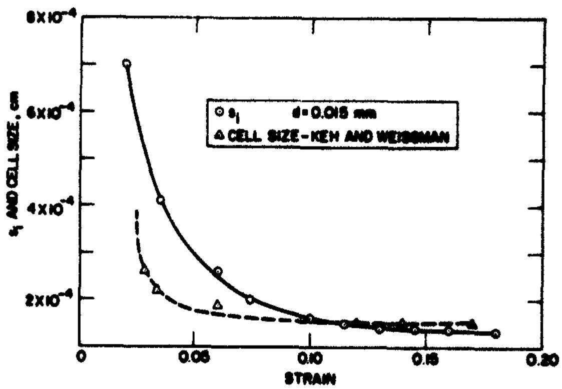

FIG. 6. COMPARISON OF THE AVERAGE DISTANCE MOVED BY DISLOCATIONS DURING EACH 1% INCREMENT OF STRAIN, s_i, WITH THE DEFORMATION CELL SIZE

Using the values of k and n determined from the data on iron, dislocation density is calculated as a function of grain size and strain for copper and silver. In Table I the calculated values of ρ are compared with independently counted values obtained from electron transmission micrographs of the

[2] ρ_t was taken from the measurements by Keh and Weissman (Ref. 2) of dislocation density as a function of strain.

deformed specimens (Refs. 5 and 6).[3] Bailey and Hirsch (Ref. 6) estimate the error in counting dislocations by this method to be 25 percent. In view of the variety of materials and data involved in the present analysis, the agreement between the calculated and observed dislocation density is surprisingly good. It is noted that agreement is poorest at the higher levels of strain, i.e., in the region where the curve relating k and strain (Fig. 4) is extrapolated. It is possible that the relationship is not linear, as was assumed, but that it asymptotically approaches a minimum value.

Table I. Comparison of Counted and Calculated Dislocation Densities

Material	Author	Strain	ρ Counted	ρ Calculated
Cu	Gordon (Ref. 5)[3]	17.5	3×10^{10}	2.2×10^{10}
		30.0	5.7×10^{10}	7.9×10^{10}
Ag	Bailey and Hirsch (Ref. 6)	11.0	2.2×10^{10}	1.0×10^{10}
		21	5.2×10^{10}	2.4×10^{10}
		32	6.8×10^{10}	8.8×10^{10}

[3] Counts on P. Gordon's copper are unpublished results of J. Bailey (see Ref. 1).

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